Propagation losses by tunnelling in barrier optical waveguides

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Summary

An analytical model is proposed in order to estimate the optical propagation losses due to tunnelling in barrier waveguides. The results are validated by means of a beam propagation method (BPM) simulations for different waveguides conditions.

Discussion

Ion beam implantation and irradiation methods are very versatile techniques to generate optical step-index waveguides due to a decrease of the index profile wherever the ions interact with the crystal creating a barrier that confines the beam. In particular they are an established way to fabricate waveguides in lithium niobate and other photo-refractive materials. They allow to control important parameters such as barrier and waveguides width [1]. In order to produce good performance integrated optical devices, it is necessary to estimate and control propagation the losses in function of these parameters.

In these waveguides, tunnelling propagation losses appear because part of the mode travels outside the barrier where $n_{eff} < n_{substrate}$ and a evanescent wave can't be a solution of the wave equation. To estimate the losses we consider a guided normalized mode of a waveguide with an infinite barrier. We focus in the fraction of the mode that remains outside the barrier of the actual system. In our model the area of the square of this fraction (A_o) is proportional to the energy that escapes from the waveguide. This area has an analytical expression for a step-index guide:

$$A_o = \frac{C^2}{2\sqrt{(n_{eff}^2 - n_b^2)}} \frac{n_g^2 - n_a^2}{n_g^2 - n_b^2} \exp(-2 b k_0 \sqrt{(n_{eff}^2 - n_b^2)}) \qquad (1)$$

where n_{eff}, n_b, n_a and n_g are the refractive index of the mode, the barrier, the air and the waveguide respectivel,. k_0 the wave vector, b the barrier width, and C a normalization factor for the total area.

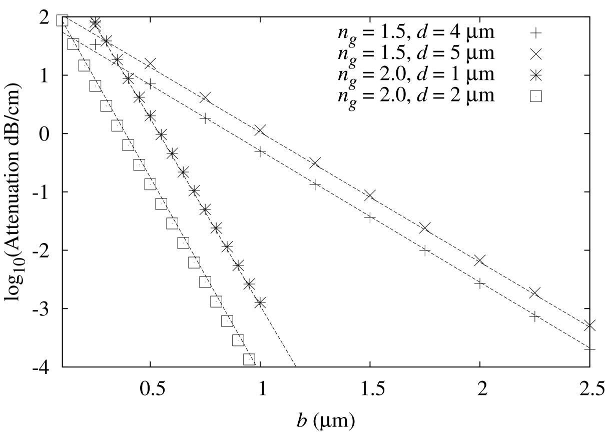

Fig.1. Attenuation calculated by eq.1 (lines) and by BPM (symbols) as function of the barrier width for different crystals.

Fig. 1 shows attenuations obtained by eq.1 *vs* the barrier width. BPM results are plotted for several wave-guides for comparison. The exponential dependence from eq.1 is perfectly validated for different guide widths and n_g values. When the barrier becomes very thin both values slightly disagree, however, at this point, the high attenuation values makes the guide useless for optical devices.

The dependence of the attenuation with other different guide parameters (as width and depth) have also been analyzed. The difference n_{eff}-$n_{substrate}$ has been found to be the most relevant parameter, according with the observation that high order modes present greater losses and larger A_o values. Guide width variation affects attenuation via modification of n_{eff}-$n_{substrate}$ for a given mode.

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References

[1] F. Chen, X. L. Wang and K. M. Wang, “Development of ion-implanted optical waveguides in optical materials: A review”, *Optical Materials* **29** 1523-1542, 2007.

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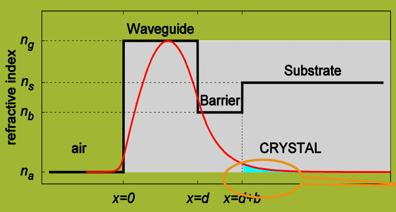
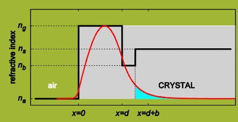
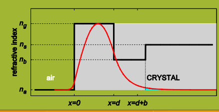
This work studies tunnelling, fluctuation of refractive index and fluctuations of the waveguide width as mechanisms of generation of propagation losses in barrier optical waveguides. The studied is carried out with beam propagation method simulations. Moreover, a simple model is proposed to describe the attenuation by tunneling.

Model





$\propto$ **Tunnelling losses**



Tunnelling losses throught the off-barrier area

Losses are proportional to the fraction of the beam area outside the barrier

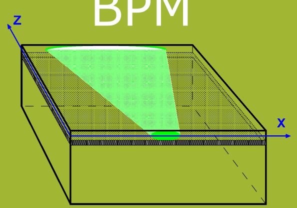
$$A_0 = \int_{d+b}^{\infty} E(x)E^*(x)dx$$

$$E(x) = \begin{cases} Ce^{k_0\sqrt{n_m^2-n_a^2}x} & x \le 0 \\ C\sqrt{\frac{{n_g}^2-{n_a}^2}{{n_g}^2-{n_m}^2}}\sin\left(k_o\sqrt{(n_g^2-n_m^2)}x+\theta\right) & 0<x<d \\ C\sqrt{\frac{{n_g}^2-{n_a}^2}{{n_g}^2-{n_b}^2}}e^{-k_o\sqrt{n_m^2-n_b^2}(x-d)} & x \ge d \end{cases}$$

$$\frac{d^2E_y(x)}{dx^2} + [{k_0}^2n^2(x) - {n_m}^2]E_y(x) = 0$$

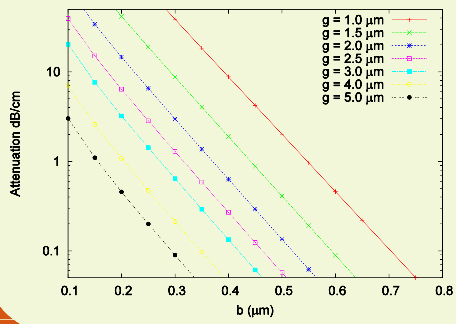
$$A_0 = \frac{C^2}{2\sqrt{{n_m}^2-{n_b}^2}}\frac{{n_g}^2-{n_a}^2}{{n_g}^2-{n_b}^2}e^{-2bk_0\sqrt{{n_m}^2-{n_b}^2}}$$

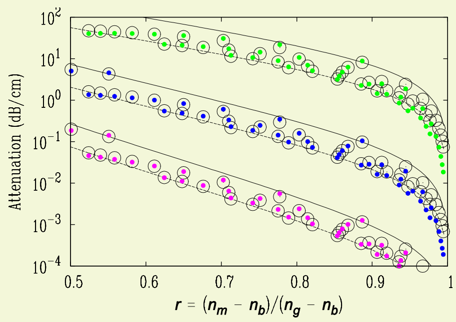
BPM



Simulation of the beam propagation by the discrete solution of the previous equations

Comparison between A_0 and BPM simulations

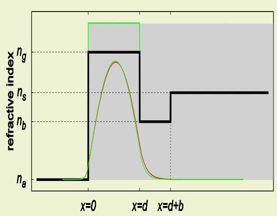




r= burial depth.
r=0 → $n_m \approx n_b$ → superficial
r=1 → $n_m \approx n_g$ → deep

Other sources of losses: fluctuactions

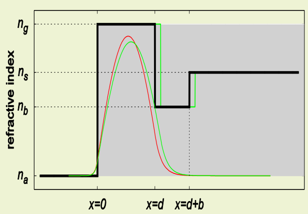
Refractive index



Negligibles differences between both modes

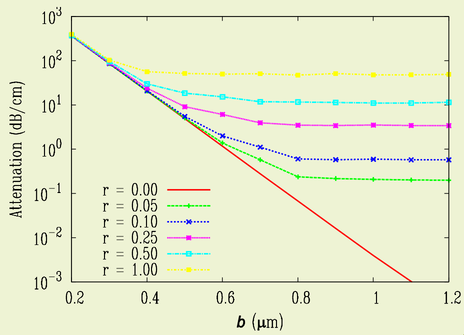
Most of the old mode …

Waveguide width



Small differences between both modes

Only a portion of the old mode …



Satisfy the new wave equation

An study of mechanisms that produces propagation losses in optical waveguides with a barrier has been carried out. The effect of tunnelling and the fluctuation of the refractive index and of the waveguide width has been studied as function of the barrier width. The fluctuation in the waveguide width shows a relevant production of losses in comparison width the other mechanism. And this appears to be independent of the barrier with, only depends on the wall roughness. Moreover, a model was proposed for explain the tunnelling losses, finding a good agreement with the simulations.

[1] F. Chen, X. L. Wang and K. M. Wang, "Development of ion-implanted optical waveguides in optical materials: A review", *Optical Materials* **29** 1523-1542, 2007.
[2] T. Plsika, C. Fluck, P. Gun ter, L. Beckers, C. Buchal, "Mode propagatiion losses in he+ ion implanted KNbO3", J. Opt. Soc. Am. B, **15**, 628-639, 1998

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